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New Physics in Top at Tevatron

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Abstract

I report on direct and indirect searches for new physics in top events from the CDF and D0 Collaborations at the Fermilab Tevatron Collider.

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1 Introduction

The top quark is the heaviest known elementary particle, making it a natural probe for new physics. In addition, it is the only known elementary particle whose mass is near the scale of electroweak symmetry breaking, suggesting that it plays a special role there. The top quark was discovered by the CDF and D0 Collaboration in Run I of the Fermilab Tevatron Collider [1]. In Run II, the Tevatron collides protons and antiprotons with a center of mass energy of 1.96 fb^{-1} , providing large samples of top quark that enable CDF and D0 to search for signs of new physics in top quark events. The CDF and D0 detectors are described in Ref. [2].

I report on recent direct searches for processes beyond the standard model (BSM), and on indirect searches performed by measuring top quark properties which are firmly predicted in the standard model (SM), and looking for significant deviations from these predictions. Measurements of asymmetries in $t\bar{t}$ production fall into the latter category, but are reported elsewhere in these proceedings [3].

2 Searches for narrow $t\bar{t}$ resonances

Both Tevatron collaborations search for “narrow” resonances in $t\bar{t}$ production, that is, resonances in the $m_{t\bar{t}}$ spectrum with an intrinsic width that is smaller than the experimental resolution for $m_{t\bar{t}}$ [4]. This is implemented by taking the width to be 1.2% of the resonance mass.

The searches are performed in the “lepton+jets” channel, where one of the two W bosons from the $t \rightarrow Wb$ decays * decayed leptonically into $l\bar{\nu}_l$ and the other W boson decayed hadronically into $q\bar{q}'$. When the isolated lepton from the leptonic W boson decays is an electron or muon, even if produced from an intermediate τ lepton, it provides a strong experimental handle. Thus hadronic τ lepton decays are not considered as part of the signal in this channel.

Data samples are further enriched in top decays by requiring that the events contain several jets, as typically three or four jets arise from the four quarks produced in these decays, an imbalance in transverse energy (\cancel{E}_T) due to the neutrino, and displaced decay vertices typical of the hadronization and subsequent electroweak decay of the b quarks. The resulting sample compositions are shown in Fig. 1.

The background arise mainly from W +jets and multijet production. The former is enriched in heavy-flavor jets, by the requirement that jets are tagged as arising from b quarks. It is simulated using a matched tree-level Monte Carlo (MC) generator [5] coupled with the PYTHIA shower generator [6], and with the heavy-flavor content increased to match data. Other sources of background, such as single-top and di-boson production, are modeled from simulation.

*charged conjugate processes are included implicitly throughout.

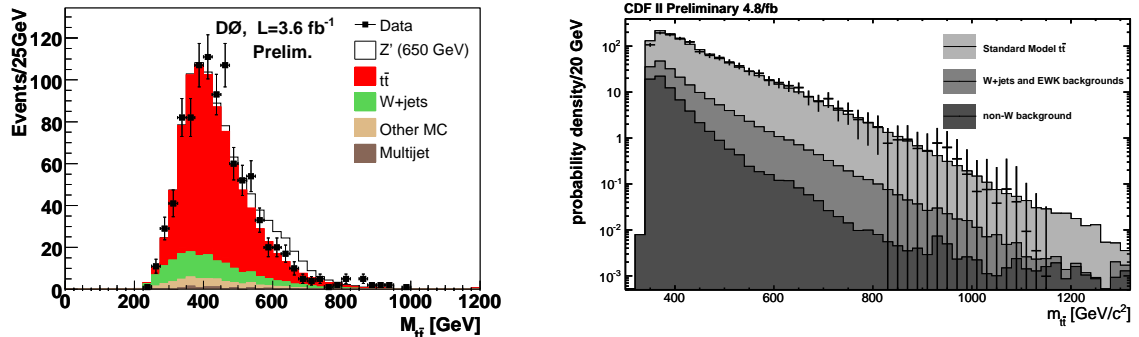


Figure 1: Reconstructed $m_{t\bar{t}}$ spectra and sample compositions from the D0 (left) and CDF (right) searches for resonant $t\bar{t}$ production.

The multijet background arises when a jet is misidentified as an isolated lepton. For example, this happens when a lepton produced in the decay of one of the jet's hadrons carries most of the jet's energy, and the rest of the jet is not reconstructed, so that the lepton is correctly reconstructed, but its identification as an isolated lepton is false. This background is modeled using auxiliary data samples.

In the D0 search, $m_{t\bar{t}}$ is taken from 4-vector sum of the jets, lepton, and neutrino candidate, where the neutrino is reconstructed from the \cancel{E}_T using the measured lepton 4-vector and the known W boson mass. This simple reconstruction technique works equally well when only three jets are selected, and these events are included in the D0 search.

In the CDF search, rather than reconstruct one $m_{t\bar{t}}$ value per event, the probability density for each $m_{t\bar{t}}$ value is calculated per event using the observed 4-vectors, the SM matrix elements for such $t\bar{t}$ production, the parton distribution functions (PDFs), and the transfer functions. The transfer functions account for the differences between the observed jets and their progenitor quarks. This includes both SM effects from Quantum Chromodynamics (QCD), such as showering and hadronization, and the experimental resolution for the detected objects. The reconstructed spectrum for each sample is then the sum of the per-event probability densities.

To increase statistical strength, each search is performed in several channels, by lepton type, number of jets, and number of b -tagged jets. Then the signal cross section is measured for each possible resonance mass using a maximal likelihood estimate, and Bayesian limits are set at the 95% (and 68%) CL. Continuum $t\bar{t}$ production is a background to the resonant production being measured, and is estimated using either matched MC (in D0) or using PYTHIA with k factors to match NLO calculations (in CDF). Systematic uncertainties are included using nuisance parameters which are integrated out in the limit setting. The results are shown in Fig. 2, together with the mass limits for a specific type of resonance. D0 exclude $M_{Z'} < 820$ GeV, while CDF

exclude $M_{Z'} < 900$ GeV.

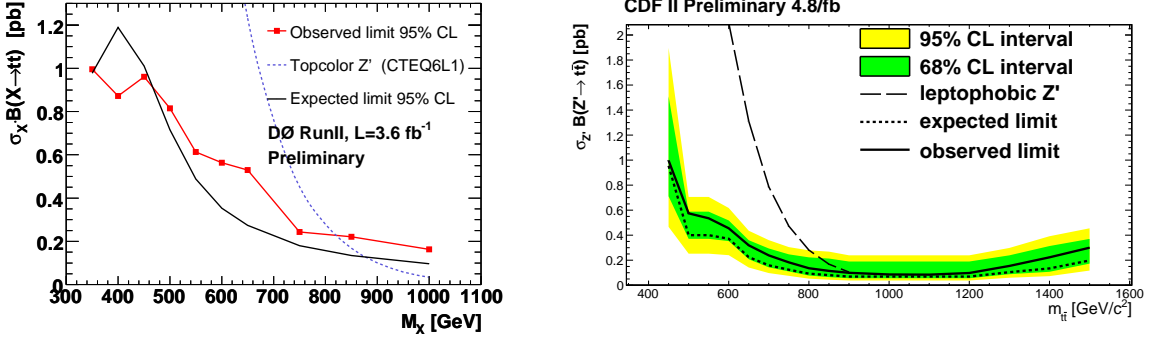


Figure 2: Reconstructed $m_{t\bar{t}}$ spectra and sample compositions from the D0 (left) and CDF (right) searches for resonant $t\bar{t}$ production.

3 Flavor-Changing Neutral Current in top decays

In the SM, flavor-changing neutral current (FCNC) decays of top quarks are extremely rare: $\text{BR}(t \rightarrow Zc)$ is of order 10^{-14} , and $\text{BR}(t \rightarrow Zu)$ is of order 10^{-17} . FCNC decays can be enhanced by BSM processes, such as SUSY or quark compositeness, which can reach branching fractions of order per mille.

In the top sector, FCNC vertices that include a gluon are constrained by D0 using single top events [7]. Those that include a Z boson were previously constrained by CDF in the $Z+4$ jets channel to have $\text{BR}(t \rightarrow Zq) < 3.7\%$, with an expected limit of 5.0% [8].

Recently, D0 published a search for FCNC decays that include a Z boson in the tri-lepton channel (diagrammed in Fig. 3), where both Z and W bosons decay leptonically [9]. This final state offers excellent background rejection, but suffers from low rates. To maximize the selection efficiency, electron candidates are considered out to $|\eta| = 2.5$, which requires a special reconstruction algorithm in the inter-cryostat region (ICR), $1.1 < |\eta| < 1.5$. The background rejection of the ICR electron candidates is relatively weak, so they are used only for the $Z \rightarrow ee$ decay, where excellent background rejection is available using the known Z boson mass. The muon coverage extends to $|\eta| = 2.0$. The sample composition is shown in Fig. 4.

D0 search for FCNC decays described by the term:

$$\mathcal{L}_{\text{FCNC}} = \frac{e}{2 \sin \theta_W \cos \theta_W} \bar{t} \gamma_\mu (v_{tqZ} - \gamma_5 a_{tqZ}) q Z^\mu + \text{h.c.}, \quad (1)$$

where e is the electron charge, θ_W is the Weinberg angle, and t , q , and Z are the fields whose quanta are the quarks and the Z boson. To test for the presence of

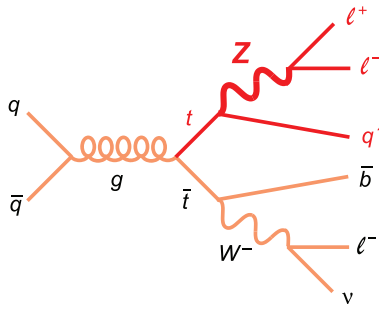


Figure 3: Feynman diagram for the tri-lepton FCNC top decay.

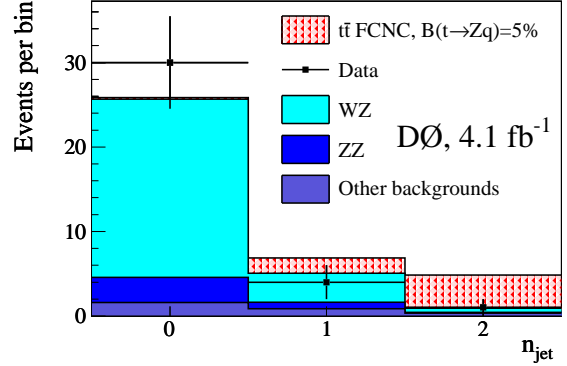


Figure 4: Number of jets and sample composition in the FCNC decay search.

signal, D0 uses the log of the ratio between the likelihood of the signal under the signal+background and the background only hypotheses. The likelihoods are calculated for nine H_T distributions, where H_T is the scalar sum of the transverse momenta (p_T) of the leptons, jets, and \cancel{E}_T in each event. These distributions are for all events with no jets, and for events with either one or more than one jets, which are divided into four ranges in reconstructed top mass (< 120 , $120\text{--}150$, $150\text{--}200$, and > 200 GeV). The separation between signal and background is demonstrated in Fig. 5.

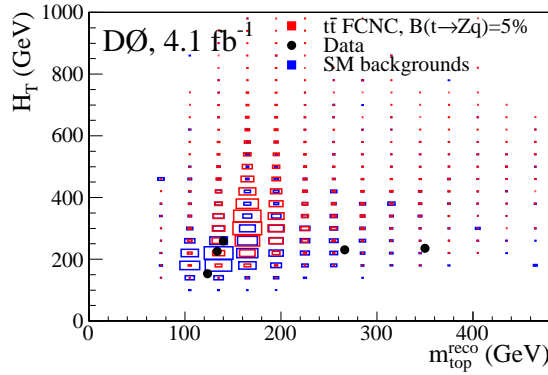


Figure 5: Discriminating variables for events with ≥ 1 jet in the FCNC decay search.

Limits are set on $\text{BR}(t \rightarrow Zq)$ using the CLs method [10], with systematic uncertainties described using nuisance parameters that are constrained to data using a generalized χ^2 test statistic [11]. The limits have only a slight dependence on the chiral structure of the resonance, which is treated as a source of systematic uncertainty so that the limits apply to resonances of any chiral structure. D0 find a limit of $\text{BR} < 3.2\%$, with an expected limit of 3.8% .

4 $W' \rightarrow tb$ search

The D0 Collaboration published a search for a heavy copy of the W boson, a W' [12]. The interaction between the W' boson and the SM is given, in the most general form of lowest dimension, by the term

$$\mathcal{L}_{W'} = \frac{V_{ij}g_w}{2\sqrt{2}}\bar{f}_i\gamma_\mu\left[a_{ij}^R(1+\gamma^5)+a_{ij}^L(1-\gamma^5)\right]W'^\mu f_j + \text{h.c.}, \quad (2)$$

where V is the CKM matrix for quarks and the identity matrix for leptons, g_w is the SM weak coupling constant, and a^L and a^R are the left- and right-handed couplings of the W' field (whose quanta is the W' boson) and the fermion doublet fields, f . The left-handed coupling are motivated by the possibility of Kaluza-Klein (KK) excitation of a W boson, which would have the same couplings as the W boson of the SM. The right-handed couplings are motivated by left-right symmetric models, which imply that the W' couples dominantly to right-handed fermions.

The search is for the process $p\bar{p} \rightarrow W'X; W' \rightarrow tb; t \rightarrow Wb; W \rightarrow l\nu$. This process is similar to the SM s-channel single top production but the intermediate boson is a W' rather than an off-shell W . Thus this search builds upon D0's single top observation [13], using a dataset corresponding to 2.3fb^{-1} of integrated luminosity. The same 24 channels are used, with the data divided by lepton flavor, number of jets, number of b -tags, and data taking period. As in Ref. [13], single top production is identified using boosted decision tree discriminants. The discriminants combine 49 input variables, and were trained using $a^L = a^R = 1$ for each channel and for each W' mass considered. The resulting discrimination and the sample composition are shown in Fig. 6.

Limits are set using a Bayesian procedure at 95% CL for generic W' mass and couplings (shown in Fig. 7) and for standard benchmark scenarios. For left handed W' boson, where the interference with the SM accounts for up to a third of the production and is fully taken into account, D0 find $M_{W'} > 863\text{GeV}$. For right handed W' bosons, the limit can depend on whether the existence of a right-handed neutrino with a mass below the W' mass. This proves to be a small effect: the limit is $M_{W'} > 885\text{GeV}$ for $m(\nu_R) < M_{W'}$ and $M_{W'} > 890\text{GeV}$ otherwise. For $a^L = a^R = 1$ the limit is $M_{W'} > 885\text{GeV}$.

5 Measurement of the top quark charge

When reconstructing the $t\bar{t}$ final state, the b quark is combined with the W^+ boson candidate (i.e. a combination of qq' or $l\nu$) and the \bar{b} with the W^- to form top quarks with an electric charge of $\pm\frac{2}{3}e$. This can be seen as a working assumption, as in most measurements there is no attempt to distinguish between the b jet and \bar{b} jet.

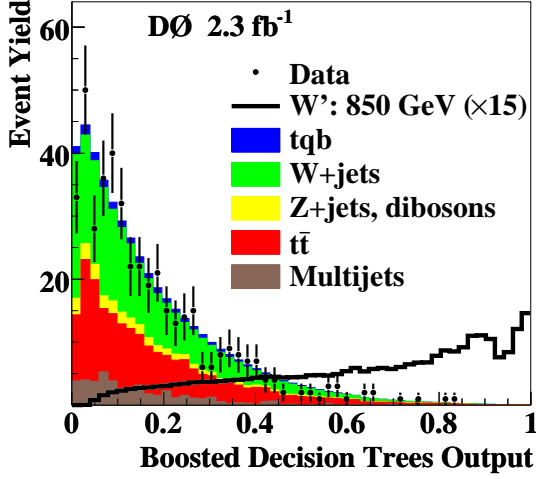


Figure 6: Discriminant for W' search and sample composition.

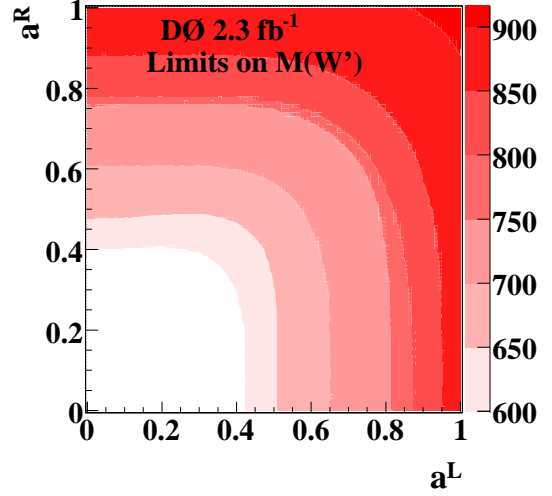


Figure 7: Limits on W' boson mass (in GeV) as a function of its couplings.

Thus an alternative was suggested in 1998 [14] that the particle found with mass ≈ 172 GeV has charge $\pm \frac{4}{3}e$, so that the real top quark is heavier and the standard reconstructions are wrong. Though this scenario has since been disfavored, we seek direct experimental evidence that refutes it.

CDF recently reported [15] a preliminary study of a more generic scenario, where only a fraction of the particles of mass ≈ 172 GeV (that decayed to bW) have a charge of $\pm \frac{4}{3}e$. To measure the fraction of these exotic particles, f_+ , the W boson candidates and the b -tagged jets are matched using a kinematic fit, and b jets are separated from \bar{b} jets using a jet charge.

The measurement was done in the lepton+jets channel. To reduce the number of possible jet-parton assignments, and thus improve the matching between b jets and W boson candidates, only events with two b tags are used in this study.

In the kinematic fit, the 4-vectors of the observed objects are varied according to their experimental resolutions and under the constraints of the known W boson and top quark masses. A χ^2 test statistic is minimized over all possible jet-parton assignments. Only events where a good assignment, with $\chi^2 < 9$, was found are analyzed further. The efficiency of this cut is 53%, and 83% of the selected assignments are correct.

The jet charge is defined as

$$Q = \frac{\sum_i (\vec{p}_i \cdot \vec{p}_j)^{0.5} Q_i}{\sum_i (\vec{p}_i \cdot \vec{p}_j)^{0.5}}, \quad (3)$$

where i runs over the tracks in the jet, with Q_i the charge and \vec{p}_i the momentum 3-vector of the jet's i -th track, and \vec{p}_j is the jet momentum 3-vector.

The performance of the jet charge was calibrated using control data enriched in $b\bar{b}$ events with a tag and probe technique, and in eight bins of jet transverse energy. The enrichment was done by b tagging both jets using displaced vertices, and by requiring a tag muon in one of the jets. The charge of the muon tags, with an easily-modeled accuracy, the flavor of the jet that contains it. The purity of the samples is evaluated using the p_T of the muon relative to the axis of the tag jet and using the mass of the displaced vertex in the probe jet. The jet charge correctly identifies whether a jet originated from a b or \bar{b} quark 61% of the time. The distribution of the jet charge, multiplied by charge of the W boson matched to it so as to reconstruct the sign of their progenitor top quark, is shown in Fig. 8.

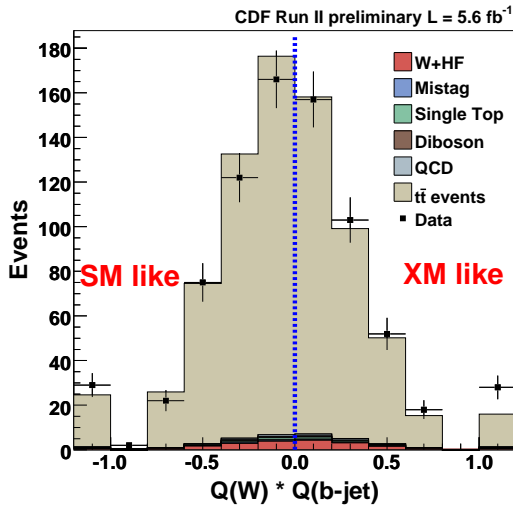


Figure 8: Distributions of jet charge signed by W boson charge and sample composition. “XM” refers to the exotic particle scenario described in the text.

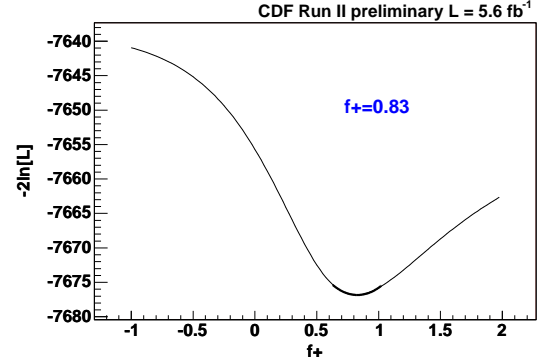


Figure 9: Profile likelihood as a function of $f+$.

The likelihood for each event is calculated, accounting for b -jet misidentification and/or mistaken jet–parton assignments, as a function of $f+$. To measure $f+$ a profile likelihood test statistic is built from the per-event likelihoods by maximizing the sample likelihood with respect to the sources of systematic uncertainty, represented by nuisance parameters. The profile likelihood as a function of $f+$ is shown in Fig. 9.

The measured value is consistent with the SM, with a p value of 0.134, but is inconsistent with the exotic charge ($\pm\frac{4}{3}e$) scenario, with a p value of $1.4 \cdot 10^{-4}$. Thus the alternative scenario of Ref. [14] is ruled out at the 95% CL. This preference for the SM was also quantified in terms of a Bayes factor. CDF find $2 \ln BF = 19.6$, that

is, that the data favors the SM very strongly.

6 W boson helicity in top quark decays

The SM predicts $\text{BR}(t \rightarrow bW^+) > 99.8\%$, which is supported by measurements so far [16]. This prediction can be broken down by helicity states: the prediction for the fraction of left-handed W^+ bosons in this decay is $f_- = 31.1\%$, for the fraction of longitudinally-polarized W^+ s $f_0 = 68.7\%$, and for the fraction of right-handed W^+ s $f_+ = 0.17\%$ [17]. The latter is suppressed due to the $V - A$ nature of charged weak current interactions. The experimental uncertainties are smaller than the uncertainties on these calculation, so the measurements can not be used to constrain the parameters of the SM. Instead they serve to probe for effects beyond the SM.

We distinguish between the helicity states by reconstructing $\cos\theta^*$, the angle between the direction from which the top quark entered the decay and the direction of the outgoing up type fermion in the W boson's rest frame. The distributions of $\cos\theta^*$ for various helicity states are shown in Fig. 10.

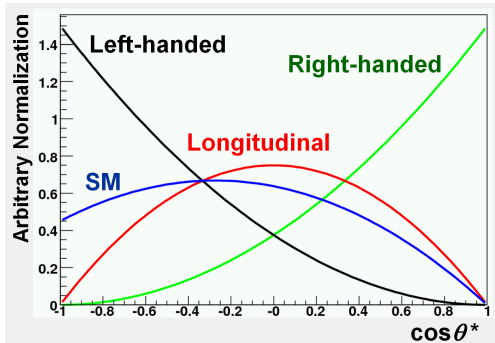


Figure 10: Distributions of production-level $\cos\theta^*$ for the different helicity states and the SM.

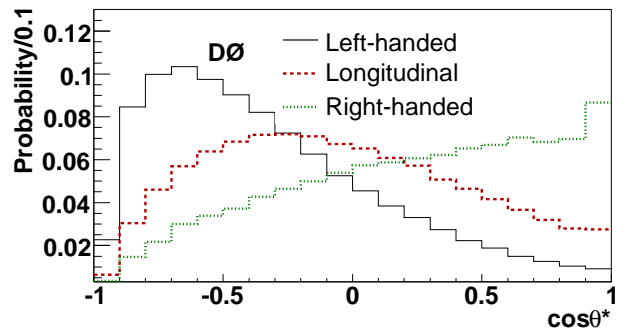


Figure 11: Distributions of the reconstructed $\cos\theta^*$ for the different helicity states and the SM in the lepton+jet channel in D0.

The D0 Collaboration recently published [18] a measurement of the W helicity. The measurement was performed in both the lepton+jet channel and in the dilepton channel, where both W bosons in $t\bar{t} \rightarrow W^+bW^-\bar{b}$ decay leptonically.

In the lepton+jet channel, selection and reconstruction, through a kinematic fitter, are similar to those described above. In particular, a discriminant is used to enrich the data in $t\bar{t}$ events. The excellent reconstruction of $\cos\theta^*$ from the leptonically decaying top quark can be seen by comparing Figs. 10 and 11. The deficit seen in Fig. 11 at $\cos\theta^* \approx -1$ is due to acceptance effects rather than imperfect reconstruction. In that region the angular separation between the lepton and the b jet (from the same $t \rightarrow Wb$ decay) is too small for them to be reconstructed as separate objects. For the

hadronically decaying top quark, only $|\cos \theta^*|$ can be reconstructed, since the flavor of the jets is not readily available. Nevertheless, the information from the hadronically decaying top quarks is useful to constrain f_0 .

In the dilepton channel, events are selected if they contain two isolated leptons (again this refers to electrons and muons, possibly through an intermediate τ lepton) of opposite charge and at least two jets. Discriminants are built for each channel (ee , $e\mu$ and $\mu\mu$) and used to enrich the data in $t\bar{t}$ events. Due to the two unmeasured neutrinos, the kinematics of the system are under constrained. A probabilistic reconstruction is used: the objects are varied within their experimental resolutions and for each variation the mass constraints are used to find the possible neutrino momenta. Up to eight solutions are possible. The two $\cos \theta^*$ values are calculated for each solution in 500 variations of the objects, and their averages are the reconstructed $\cos \theta^*$ values. The resulting separation is somewhat weaker than in the lepton+jets channel.

The CDF Collaboration has recently measured the W helicity in the dilepton channel using a similar technique [19]. Notable differences are: (a) instead of using custom discriminants, CDF enrich the data in $t\bar{t}$ using b tagging, and (b) CDF use additional criteria to select the most likely solution out of the up to eight solution for each variation.

In both analyses, the W helicity fractions are extracted by fitting a linear sum of the templates for each helicity state (e.g. those shown in Fig. 11) and for background to data. The results of the fits are shown in Fig. 12. CDF then further calibrates their method, finding corrections of 1–2% which yield $f_0 = 0.78 \pm 0.20$ and $f_+ = -0.12 \pm 0.10$. D0 find $f_0 = 0.67 \pm 0.10$ and $f_+ = 0.02 \pm 0.05$.

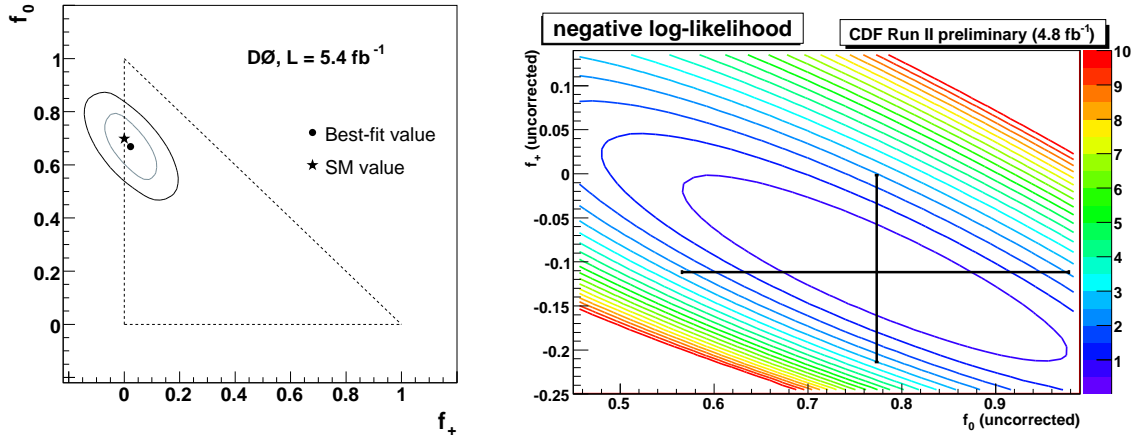


Figure 12: Fitted W boson helicities in top decays from D0 (left) and CDF (right). Note the different axis definitions. In the left plot, the dashed triangle shows the physically allowable region, while the blue and black curves show the 1σ and 2σ contours. In the right plot, the black lines represent the statistical uncertainties, and the colored lines show contours.

7 Direct measurement of the $t\text{--}\bar{t}$ mass difference

From the CPT theorem we learn that for any canonical [†] quantum field theory, the mass of particles and their antiparticle are identical. Due to QCD color confinement, quark masses are not directly accessible. The only exception is the top quark, which decays before it is confined. Both collaborations measure the mass difference between top and antitop quarks [20], as a probe for BSM effects.

The mass difference is measured in the lepton+jets channel, with at least one b -tagged jet. The charge of the lepton separates the top from the antitop quark. An interesting experimental aspect is that the calorimetry's response to b and \bar{b} jets may differ.

The D0 measurement was a variation of their mass measurement using the matrix element technique [21], with the signal generated a modified version of PYTHIA. They find $m_t - m_{\bar{t}} = 3.8 \pm 3.7 \text{ GeV}$, as shown in Fig. 13 for each lepton flavor.

The more recent CDF measurement uses a much larger data sample. Signal is generated using MADGRAPH [22] and the events are reconstructed using a kinematical fitter. Unlike the analyses described above, in this analysis for each event the two best solution are retained (see Fig. 14). The mass difference is measured with an unbinned likelihood fit with the data split into channels by the number of b tags. CDF find $m_t - m_{\bar{t}} = -3.3 \pm 1.7 \text{ GeV}$.

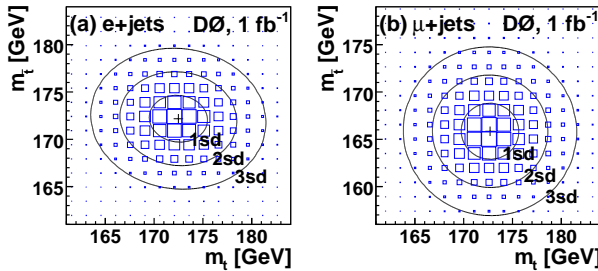


Figure 13: Likelihood of $m_t, m_{\bar{t}}$ from D0. The black curves show contours of equal probability.

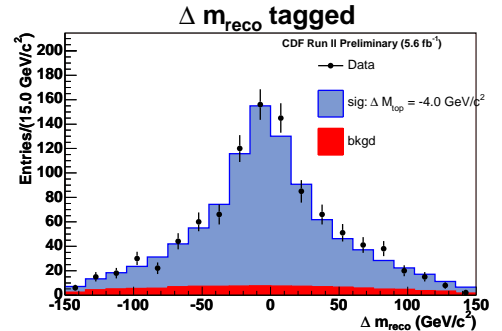


Figure 14: Reconstructed mass difference from CDF.

8 Conclusion and Summary

The standard model describes Tevatron top data well, with a caveat presented in Ref. [3]. The Tevatron experiments search for a wide variety of new physics in top

[†]local, Lorentz-covariant, and with a Hamiltonian that is bounded from below

events, using both direct and indirect searches. The latest examples were reported here.

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